

# Table of Contents

---

<b>Preface</b>	<b>v</b>
<b>About the Editor</b>	<b>vii</b>
<b>About the Authors</b>	<b>ix</b>
<b>Acknowledgments</b>	<b>xv</b>
<b>Chapter 1 Overview of Steelmaking Processes and Their Development</b>	<b>1</b>
1.1 Introduction	1
1.2 Historical Development of Modern Steelmaking	1
1.2.1 Bottom-Blown Acid or Bessemer Process	2
1.2.2 Basic Bessemer or Thomas Process	4
1.2.3 Open Hearth Process	4
1.2.4 Oxygen Steelmaking	7
1.2.5 Electric Furnace Steelmaking	8
1.3 Evolution in Steelmaking by Process	10
1.4 Structure of This Volume	12
<b>Chapter 2 Fundamentals of Iron and Steelmaking</b>	<b>13</b>
2.1 Thermodynamics	13
2.1.1 Ideal Gas	13
2.1.2 Thermodynamic Laws	14
2.1.3 Thermodynamic Activity	18
2.1.4 Reaction Equilibrium Constant	23
2.2 Rate Phenomena	24
2.2.1 Diffusion	24
2.2.2 Mass Transfer	26
2.2.3 Chemical Kinetics	39
2.2.4 Mixed Control	47
2.3 Properties of Gases	49
2.3.1 Thermochemical Properties	49

2.3.2 Transport Properties	55
2.3.3 Pore Diffusion	57
2.4 Properties of Molten Steel	60
2.4.1 Selected Thermodynamic Data	60
2.4.2 Solubility of Gases in Liquid Iron	61
2.4.3 Iron-Carbon Alloys	64
2.4.4 Liquidus Temperatures of Low Alloy Steels	69
2.4.5 Solubility of Iron Oxide in Liquid Iron	69
2.4.6 Elements of Low Solubility in Liquid Iron	70
2.4.7 Surface Tension	72
2.4.8 Density	75
2.4.9 Viscosity	75
2.4.10 Diffusivity, Electrical and Thermal Conductivity, and Thermal Diffusivity	76
2.5 Properties of Molten Slags	79
2.5.1 Structural Aspects	79
2.5.2 Slag Basicity	80
2.5.3 Iron Oxide in Slags	81
2.5.4 Selected Ternary and Quaternary Oxide Systems	81
2.5.5 Oxide Activities in Slags	84
2.5.6 Gas Solubility in Slags	89
2.5.7 Surface Tension	95
2.5.8 Density	98
2.5.9 Viscosity	100
2.5.10 Mass Diffusivity, Electrical Conductivity and Thermal Conductivity	101
2.5.11 Slag Foaming	102
2.5.12 Slag Models and Empirical Correlations for Thermodynamic Properties	104
2.6 Fundamentals of Ironmaking Reactions	104
2.6.1 Oxygen Potential Diagram	104
2.6.2 Role of Vapor Species in Blast Furnace Reactions	105
2.6.3 Slag-Metal Reactions in the Blast Furnace	109
2.7 Fundamentals of Steelmaking Reactions	118
2.7.1 Slag-Metal Equilibrium in Steelmaking	119
2.7.2 State of Reactions in Steelmaking	123
2.8 Fundamentals of Reactions in Electric Furnace Steelmaking	132
2.8.1 Slag Chemistry and the Carbon, Manganese, Sulfur and Phosphorus Reactions in the EAF	132
2.8.2 Control of Residuals in EAF Steelmaking	134
2.8.3 Nitrogen Control in EAF Steelmaking	135
2.9 Fundamentals of Stainless Steel Production	136
2.9.1 Decarburization of Stainless Steel	136
2.9.2 Nitrogen Control in the AOD	138
2.9.3 Reduction of Cr from Slag	139
2.10 Fundamentals of Ladle Metallurgical Reactions	140
2.10.1 Deoxidation Equilibrium and Kinetics	140
2.10.2 Ladle Desulfurization	147
2.10.3 Calcium Treatment of Steel	150
2.11 Fundamentals of Degassing	151
2.11.1 Fundamental Thermodynamics	151
2.11.2 Vacuum Degassing Kinetics	152

<b>Chapter 3 Steel Plant Refractories</b>	<b>159</b>
3.1 Classification of Refractories	159
3.1.1 Magnesite or Magnesite–Lime Group	160
3.1.2 Magnesite–Chrome Group	163
3.1.3 Siliceous Group	164
3.1.4 Clay and High-Alumina Group	166
3.1.5 Processed Alumina Group	169
3.1.6 Carbon Group	170
3.2 Preparation of Refractories	172
3.2.1 Refractory Forms	172
3.2.2 Binder Types	173
3.2.3 Processing	176
3.2.4 Products	177
3.3 Chemical and Physical Characteristics of Refractories and their Relation to Service Conditions	178
3.3.1 Chemical Composition	178
3.3.2 Density and Porosity	179
3.3.3 Refractoriness	181
3.3.4 Strength	182
3.3.5 Stress-Strain Behavior	185
3.3.6 Specific Heat	186
3.3.7 Emissivity	187
3.3.8 Thermal Expansion	188
3.3.9 Thermal Conductivity and Heat Transfer	190
3.3.10 Thermal Shock	194
3.4 Reactions at Elevated Temperatures	194
3.5 Testing and Selection of Refractories	206
3.5.1 Simulated Service Tests	206
3.5.2 Post-Mortem Studies	212
3.5.3 Thermomechanical Behavior	213
3.6 General Uses of Refractories	215
3.6.1 Linings	215
3.6.2 Metal Containment, Control and Protection	217
3.6.3 Refractory Use for Energy Savings	222
3.7 Refractory Consumption, Trends and Costs	224
 <b>Chapter 4 Steelmaking Refractories</b>	 <b>227</b>
4.1 Refractories for Oxygen Steelmaking Furnaces	227
4.1.1 Introduction	227
4.1.2 Balancing Lining Wear	228
4.1.3 Zoned Linings by Brick Type and Thickness	230
4.1.4 Refractory Construction	231
4.1.5 Furnace Burn-In	235
4.1.6 Wear of the Lining	235
4.1.7 Lining Life and Costs	238
4.2 BOF Slag Coating and Slag Splashing	239
4.2.1 Introduction	239

4.2.2 Slag Coating Philosophy	239
4.2.3 Magnesia Levels and Influences	239
4.2.4 Material Additions	240
4.2.5 Equilibrium Operating Lining Thickness	240
4.2.6 Other Refractory Maintenance Practices	241
4.2.7 Laser Measuring	241
4.2.8 Slag Splashing	241
4.3 Refractories for Electric Furnace Steelmaking	243
4.3.1 Electric Furnace Design Features	243
4.3.2 Electric Furnace Zone Patterns	244
4.3.3 Electric Furnace Refractory Wear Mechanisms	247
4.3.4 Conclusion	248
4.4 Refractories for AOD and VOD Applications	248
4.4.1 Background	248
4.4.2 AOD Refractories	249
4.4.3 VOD Refractories	258
4.4.4 Acknowledgments	261
4.5 Refractories for Ladles	262
4.5.1 Function of Modern Steel Ladle	262
4.5.2 Ladle Design	265
4.5.3 Ladle Refractory Design and Use	268
4.5.4 Ladle Refractory Construction	276
4.5.5 Refractory Stirring Plugs	277
4.5.6 Refractory Life and Costs	281
4.6 Refractories for Degassers	285

## **Chapter 5 Production and Use of Industrial Gases for Iron and Steelmaking**

**291**

5.1 Industrial Gas Uses	291
5.1.1 Introduction	291
5.1.2 Oxygen Uses	292
5.1.3 Nitrogen Uses	294
5.1.4 Argon Uses	295
5.1.5 Hydrogen Uses	296
5.1.6 Carbon Dioxide Uses	296
5.2 Industrial Gas Production	297
5.2.1 Introduction	297
5.2.2 Atmospheric Gases Produced by Cryogenic Processes	298
5.2.3 Atmospheric Gases Produced by PSA/VSA/VPSA Membranes	302
5.2.4 Hydrogen Production	305
5.2.5 Carbon Dioxide Production	305
5.3 Industrial Gas Supply System Options and Considerations	306
5.3.1 Introduction	306
5.3.2 Number of Gases	306
5.3.3 Purity of Gases	307
5.3.4 Volume of Gases	307
5.3.5 Use Pressure	307
5.3.6 Use Pattern	307
5.3.7 Cost of Power	307

5.3.8 Backup Requirements	307
5.3.9 Integration	307
5.4 Industrial Gas Safety	307
5.4.1 Oxygen	308
5.4.2 Nitrogen	308
5.4.3 Argon	308
5.4.4 Hydrogen	309
5.4.5 Carbon Dioxide	309
<b>Chapter 6 Steel Plant Fuels and Water Requirements</b>	<b>311</b>
6.1 Fuels, Combustion and Heat Flow	311
6.1.1 Classification of Fuels	311
6.1.2 Principles of Combustion	312
6.1.3 Heat Flow	326
6.2 Solid Fuels and Their Utilization	329
6.2.1 Coal Resources	330
6.2.2 Mining of Coal	336
6.2.3 Coal Preparation	339
6.2.4 Carbonization of Coal	341
6.2.5 Combustion of Solid Fuels	341
6.3 Liquid Fuels and Their Utilization	344
6.3.1 Origin, Composition and Distribution of Petroleum	345
6.3.2 Grades of Petroleum Used as Fuels	347
6.3.3 Properties and Specifications of Liquid Fuels	348
6.3.4 Combustion of Liquid Fuels	351
6.3.5 Liquid-Fuel Burners	351
6.4 Gaseous Fuels and Their Utilization	352
6.4.1 Natural Gas	353
6.4.2 Manufactured Gases	353
6.4.3 Byproduct Gaseous Fuels	356
6.4.4 Uses for Various Gaseous Fuels in the Steel Industry	358
6.4.5 Combustion of Various Gaseous Fuels	360
6.5 Fuel Economy	363
6.5.1 Recovery of Waste Heat	364
6.5.2 Minimizing Radiation Losses	366
6.5.3 Combustion Control	366
6.5.4 Air Infiltration	367
6.5.5 Heating Practice	368
6.6 Water Requirements for Steelmaking	368
6.6.1 General Uses for Water in Steelmaking	368
6.6.2 Water-Related Problems	371
6.6.3 Water Use by Steelmaking Processes	372
6.6.4 Treatment of Effluent Water	379
6.6.5 Effluent Limitations	385
6.6.6 Boiler Water Treatment	395
<b>Chapter 7 Pre-Treatment of Hot Metal</b>	<b>413</b>
7.1 Introduction	413
7.2 Desiliconization and Dephosphorization Technologies	413

7.3 Desulfurization Technology	416
7.3.1 Introduction	416
7.3.2 Process Chemistry	417
7.3.3 Transport Systems	421
7.3.4 Process Venue	422
7.3.5 Slag Management	423
7.3.6 Lance Systems	424
7.3.7 Cycle Time	426
7.3.8 Hot Metal Sampling and Analysis	426
7.3.9 Reagent Consumption	426
7.3.10 Economics	427
7.3.11 Process Control	427
7.4 Hot Metal Thermal Adjustment	427
7.5 Acknowledgments	428
7.6 Other Reading	428

## **Chapter 8 Oxygen Steelmaking Furnace Mechanical Description and Maintenance Considerations 431**

8.1 Introduction	431
8.2 Furnace Description	431
8.2.1 Introduction	431
8.2.2 Vessel Shape	433
8.2.3 Top Cone-to-Barrel Attachment	434
8.2.4 Methods of Top Cone Cooling	435
8.2.5 Vessel Bottom	438
8.2.6 Types of Trunnion Ring Designs	438
8.2.7 Methods of Vessel Suspension	439
8.2.8 Vessel Imbalance	445
8.2.9 Refractory Lining Design	446
8.2.10 Design Temperatures	448
8.2.11 Design Pressures and Loading	451
8.2.12 Method of Predicting Vessel Life	457
8.2.13 Special Design and Operating Considerations	458
8.3 Materials	460
8.4 Service Inspection, Repair, Alteration and Maintenance	460
8.4.1 BOF Inspection	460
8.4.2 BOF Repair and Alteration Procedures	462
8.4.3 Repair Requirements of Structural Components	463
8.4.4 Deskulling	464
8.5 Oxygen Lance Technology	465
8.5.1 Introduction	465
8.5.2 Oxidation Reactions	465
8.5.3 Supersonic Jet Theory	466
8.5.4 Factors Affecting BOF Lance Performance	468
8.5.5 Factors Affecting BOF Lance Life	469
8.5.6 New Developments in BOF Lances	470
8.6 Sub-Lance Equipment	471

<b>Chapter 9 Oxygen Steelmaking Processes</b>	<b>475</b>
9.1 Introduction	475
9.1.1 Process Description and Events	475
9.1.2 Types of Oxygen Steelmaking Processes	476
9.1.3 Environmental Issues	477
9.1.4 How to Use This Chapter	477
9.2 Sequences of Operations—Top Blown	478
9.2.1 Plant Layout	478
9.2.2 Sequence of Operations	478
9.2.3 Shop Manning	486
9.3 Raw Materials	489
9.3.1 Introduction	489
9.3.2 Hot Metal	489
9.3.3 Scrap	491
9.3.4 High Metallic Alternative Feeds	491
9.3.5 Oxide Additions	493
9.3.6 Fluxes	494
9.3.7 Oxygen	495
9.4 Process Reactions and Energy Balance	496
9.4.1 Refining Reactions in BOF Steelmaking	496
9.4.2 Slag Formation in BOF Steelmaking	498
9.4.3 Mass and Energy Balances	499
9.4.4 Tapping Practices and Ladle Additions	503
9.5 Process Variations	504
9.5.1 The Bottom-Blown Oxygen Steelmaking or OBM (Q-BOP) Process	504
9.5.2 Mixed-Blowing Processes	507
9.5.3 Oxygen Steelmaking Practice Variations	512
9.6 Process Control Strategies	515
9.6.1 Introduction	515
9.6.2 Static Models	515
9.6.3 Statistical and Neural Network Models	516
9.6.4 Dynamic Control Schemes	517
9.6.5 Lance Height Control	519
9.7 Environmental Issues	519
9.7.1 Basic Concerns	519
9.7.2 Sources of Air Pollution	519
9.7.3 Relative Amounts of Fumes Generated	521
9.7.4 Other Pollution Sources	522
9.7.5 Summary	522
 <b>Chapter 10 Electric Furnace Steelmaking</b>	 <b>525</b>
10.1 Furnace Design	525
10.1.1 EAF Mechanical Design	525
10.1.2 EAF Refractories	545
10.2 Furnace Electric System and Power Generation	551
10.2.1 Electrical Power Supply	551
10.2.2 Furnace Secondary System	554
10.2.3 Regulation	555

10.2.4 Electrical Considerations for AC Furnaces	557
10.2.5 Electrical Considerations for DC Furnaces	560
10.3 Graphite Electrodes	562
10.3.1 Electrode Manufacture	562
10.3.2 Electrode Properties	564
10.3.3 Electrode Wear Mechanisms	564
10.3.4 Current Carrying Capacity	569
10.3.5 Discontinuous Consumption Processes	569
10.3.6 Comparison of AC and DC Electrode Consumption	572
10.3.7 Development of Special DC Electrode Grades	575
10.4 Gas Collection and Cleaning	577
10.4.1 Early Fume Control Methods	577
10.4.2 Modern EAF Fume Control	579
10.4.3 Secondary Emissions Control	583
10.4.4 Gas Cleaning	586
10.4.5 Mechanisms of EAF Dust Formation	590
10.4.6 Future Environmental Concerns	590
10.4.7 Conclusions	594
10.5 Raw Materials	594
10.6 Fluxes and Additives	595
10.7 Electric Furnace Technology	597
10.7.1 Oxygen Use in the EAF	597
10.7.2 Oxy-Fuel Burner Application in the EAF	598
10.7.3 Application of Oxygen Lancing in the EAF	601
10.7.4 Foamy Slag Practice	604
10.7.5 CO Post-Combustion	605
10.7.6 EAF Bottom Stirring	615
10.7.7 Furnace Electrics	617
10.7.8 High Voltage AC Operations	617
10.7.9 DC EAF Operations	618
10.7.10 Use of Alternative Iron Sources in the EAF	621
10.7.11 Conclusions	622
10.8 Furnace Operations	622
10.8.1 EAF Operating Cycle	622
10.8.2 Furnace Charging	623
10.8.3 Melting	624
10.8.4 Refining	624
10.8.5 Deslagging	626
10.8.6 Tapping	627
10.8.7 Furnace Turnaround	627
10.8.8 Furnace Heat Balance	628
10.9 New Scrap Melting Processes	629
10.9.1 Scrap Preheating	629
10.9.2 Preheating With Offgas	630
10.9.3 Natural Gas Scrap Preheating	630
10.9.4 K-ES	631
10.9.5 Danarc Process	634
10.9.6 Fuchs Shaft Furnace	635
10.9.7 Consteel Process	642
10.9.8 Twin Shell Electric Arc Furnace	645
10.9.9 Processes Under Development	648



<b>Chapter 11 Ladle Refining and Vacuum Degassing</b>	<b>661</b>
11.1 Tapping the Steel	662
11.1.1 Reactions Occurring During Tapping	662
11.1.2 Furnace Slag Carryover	663
11.1.3 Chilling Effect of Ladle Additions	664
11.2 The Tap Ladle	665
11.2.1 Ladle Preheating	665
11.2.2 Ladle Free Open Performance	667
11.2.3 Stirring in Ladles	669
11.2.4 Effect of Stirring on Inclusion Removal	672
11.3 Reheating of the Bath	673
11.3.1 Arc Reheating	673
11.3.2 Reheating by Oxygen Injection	675
11.4 Refining in the Ladle	677
11.4.1 Deoxidation	677
11.4.2 Desulfurization	680
11.4.3 Dephosphorization	683
11.4.4 Alloy Additions	685
11.4.5 Calcium Treatment and Inclusion Modification	687
11.5 Vacuum Degassing	693
11.5.1 General Process Descriptions	694
11.5.2 Vacuum Carbon Deoxidation	694
11.5.3 Hydrogen Removal	698
11.5.4 Nitrogen Removal	701
11.6 Description of Selected Processes	705
11.6.1 Ladle Furnace	705
11.6.2 Tank Degasser	705
11.6.3 Vacuum Arc Degasser	705
11.6.4 RH Degasser	708
11.6.5 CAS-OB Process	709
11.6.6 Process Selection and Comparison	710
<b>Chapter 12 Refining of Stainless Steels</b>	<b>715</b>
12.1 Introduction	715
12.2 Special Considerations in Refining Stainless Steels	720
12.3 Selection of a Process Route	721
12.4 Raw Materials	723
12.5 Melting	724
12.5.1 Electric Arc Furnace Melting	724
12.5.2 Converter Melting	725
12.6 Dilution Refining Processes	725
12.6.1 Argon-Oxygen Decarburization (AOD) Converter Process	725
12.6.2 K-BOP and K-OBM-S	726
12.6.3 Metal Refining Process (MRP) Converter	727
12.6.4 Creusot-Loire-Uddeholm (CLU) Converter	727
12.6.5 Krupp Combined Blowing-Stainless (KCB-S) Process	728
12.6.6 Argon Secondary Melting (ASM) Converter	728

12.6.7 Sumitomo Top and Bottom Blowing Process (STB) Converter	729
12.6.8 Top Mixed Bottom Inert (TMBI) Converter	729
12.6.9 Combined Converter and Vacuum Units	729
12.7 Vacuum Refining Processes	729
12.8 Direct Stainless Steelmaking	730
12.9 Equipment for EAF-AOD Process	732
12.9.1 Vessel Size and Shape	732
12.9.2 Refractories	733
12.9.3 Tuyeres and Plugs	733
12.9.4 Top Lances	733
12.9.5 Gases	734
12.9.6 Vessel Drive System	734
12.9.7 Emissions Collection	735
12.10 Vessel Operation	735
12.10.1 Decarburization	735
12.10.2 Refining	737
12.10.3 Process Control	737
12.10.4 Post-Vessel Treatments	738
12.11 Summary	738
<b>Chapter 13 Alternative Oxygen Steelmaking Processes</b>	<b>743</b>
13.1 Introduction	743
13.2 General Principles and Process Types	743
13.3 Specific Alternative Steelmaking Processes	745
13.3.1 Energy Optimizing Furnace (EOF)	746
13.3.2 AISI Continuous Refining	748
13.3.3 IRSID Continuous Steelmaking	749
13.3.4 Trough Process	752
13.3.5 Other Steelmaking Alternatives	753
13.4 Economic Evaluation	755
13.5 Summary and Conclusions	757
<b>Index</b>	<b>761</b>